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# Flat Plate Drag Reduction in a Water Tunnel Using Riblets

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Streamwise microgroove surface modifications, known as riblets, are known to alter the structure of the turbulent boundary layer such that the skin friction drag over the surface is reduced. For this investigation, velocity profile measurements were used to calculate the drag on a flat plate, both with and without riblets, in a high-speed water tunnel. The vinyl riblet surface produced a maximum drag reduction of 8.1% $\pm$ 2.5% at a nondimensional groove spacing, $s^+$, of 13.1. If the results obtained in the laboratory can be realized for torpedoes and other submersibles, significant improvements in vehicle speed or fuel economy will be achieved.

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# NOMENCLATURE

$C_f$ = Local Skin Friction Coefficient = $\dfrac{2\tau_w}{\rho U_\infty^2}$

D = Drag force = $b\rho U_\infty^2\theta$

H = Shape factor = $\dfrac{\delta^*}{\theta}$

$Re_\theta$ = Momentum thickness Reynolds number = $\dfrac{U_\infty\theta}{\nu}$

$Re_x$ = x-distance Reynolds number = $\dfrac{U_\infty x}{\nu}$

$U_e$ = Edge velocity = $u(\delta)$

$U_\infty$ = Free-stream velocity

b = Test plate width

h = Riblet groove height

$h^+$ = Riblet groove height in wall units = $\dfrac{hU_\infty}{\nu}\sqrt{\dfrac{C_f}{2}}$

s = Riblet groove spacing

$s^+$ = Riblet groove spacing in wall units = $\dfrac{sU_\infty}{\nu}\sqrt{\dfrac{C_f}{2}}$

u(y) = x-direction mean velocity

u'(y) = Fluctuating component of x-direction velocity (standard deviation)

$u^+$ = $\dfrac{u}{U_\infty}\sqrt{\dfrac{2}{C_f}}$

x = Distance from leading edge of plate in flow direction

y = Distance above the plate

$y^+ \quad = \frac{yU_\infty}{\nu} \sqrt{\frac{C_f}{2}}$

$\delta \quad$ = Boundary layer thickness; equal to y where $u = 0.999U_\infty$

$\delta^* \quad$ = Boundary layer displacement thickness $= \int_{y=0}^{\infty} (1 - \frac{u(y)}{U_\infty})dy$

$\theta \quad$ = Boundary layer momentum thickness $= \int_{y=0}^{\infty} \frac{u(y)}{U_\infty}(1 - \frac{u(y)}{U_\infty})dy$

$\mu \quad$ = Viscosity of water

$\nu \quad$ = Kinematic viscosity of water $= \frac{\mu}{\rho}$

$\rho \quad$ = Density of water

$\tau_w \quad$ = Wall shear stress $= \mu(\frac{du}{dy})_w$

Subscripts:

c = control surface (smooth vinyl)
l = leading edge of test surface
r = riblet surface
t = trailing edge of test surface
w = wall

# INTRODUCTION

One approach to achieving drag reduction is by altering the structure of the turbulent boundary layer such that the skin friction over the surface is reduced. Reference 1 is a review of many methods that use this approach. Modification of the body surface using streamwise grooves, or riblets, is one of these methods. A few percentage points of net drag reduction will provide substantial cost savings or improved speed and endurance capabilities for aerodynamic and hydrodynamic applications.

In 1979, Michael Walsh of NASA Langley began a series of wind tunnel tests on streamwise microgrooves [references 2,3,4]. After testing a wide range of groove geometries on flat plates, he determined that sharply peaked triangular v-grooves, with height and spacing equal to 10 to 15 wall units, produced the optimum drag reduction of about 9 percent. Frank Marentic of the 3M Company recognized the opportunity for manufacturing riblets in small groove sizes for high Reynolds number application. Currently, 3M has the capability of manufacturing adhesive-backed, vinyl riblet films in a variety of groove sizes.

Based on Walsh's aerodynamic results, others have tested flat plates with v-groove surfaces in water. These include a water channel test at a flow velocity of approximately 0.3m/s ($Re_\theta$ up to 1350) using grooves machined in plexiglas. This test, performed at Lehigh University [reference 5], showed drag reduction results very similar to Walsh's results. A separate but very similar study at Lockheed-Georgia [reference 7] was not able to measure drag accurately enough to confirm these results. In 1985, 3M riblets were applied to rowing shells and tested in a towing tank at David Taylor Naval Ship Research and Development Center. The results were widely variable and tended to indicate a degradation of the riblets from one day to the next. From a series of rowing tests, however, it was determined that the vinyl riblets reduced the boat drag by 2 percent [reference 8].

The Lehigh University facility was also used for flow visualization of the boundary layer, the results of which provide a basis for a discussion of how riblets cause drag reduction [references 5 and 6]. The increased surface area of a grooved surface compared to a smooth surface may intuitively indicate an increase, rather than decrease, in skin friction. It is believed, however, that the sharp peaks of the v-grooves serve to break up the streamwise vortices, inhibiting low-speed streak formation. In this way, the turbulent momentum exchange and skin friction would be reduced.

The present work applies 3M riblets in the turbulent boundary layer region of a flat plate in a high-speed water tunnel. The skin friction drag is calculated from velocity profile data. Momentum thickness Reynolds numbers ranged from 1260 to 7040. Spanwise measurements both upstream and downstream of the riblet surface are performed to ensure that the results are not biased by a spanwise nonuniformity. The effect of riblets on the boundary layer structure are examined through mean velocity and turbulence profiles.

# EXPERIMENTAL APPARATUS

## TEST FACILITY

The experiment was conducted in the Naval Ocean Systems Center (NOSC) high speed, open jet, recirculating water tunnel. The test section is 1m long, with a 0.31m/s diameter jet, and a turbulence level, $u'/U_e$, less than 0.25% for speeds up to 12m/s. The flat plate model was mounted on longitudinal supports, outside of the jet, in a horizontal position along the centerline. The test plate and its leading edge were separately constructed from type 302 stainless steel. The flat plate is 19.0mm thick and 0.58m wide, with an overall length of 0.86m. The leading edge piece has a streamwise length of 0.15m and a width of 0.30m and was machined to include a rounded edge with a 1.6mm high forward facing step. The step was designed to act as a tripping device, and the leading edge was placed in the water tunnel's contraction section in order to obtain as long a test plate as possible. A diagram of the test plate is shown in figure 1.

Velocity field measurements were made using a TSI Laser Doppler Velocimeter (LDV) mounted on a three-dimensional traverse with numerically controlled positioning. The LDV was operated in the backward scatter mode using a 1 W Argon-Ion laser. The transmitting and receiving optics were positioned at an angle of approximately 1 degree (pointing toward the plate) instead of the usual arrangement of the system parallel to the test plate. This configuration reduces the interference between the laser beams and the flat plate, enabling velocities to be measured as close as 0.05mm from the plate. Velocities at 20 or more y-locations were measured for each boundary layer profile.

## RIBLET GEOMETRY

The vinyl riblet film used in the tests was manufactured by the 3M Company. A single geometry of v-groove riblets was tested. The grooves have height (h) equal to spacing (s) equal to 0.0762mm (0.003 inch). The total film thickness measured to the peaks of the grooves is 0.1524mm. A plain vinyl film, 0.0762mm thick, was used as a control surface. Since the vinyl riblets were originally developed for use in air, photomicrographs were taken of the materials after soaking overnight in water. The photographs showed no swelling or visible changes between the water-soaked and dry riblets. A photomicrograph of the riblet cross-section looking in the flow direction is shown in figure 2. When drag measurements were made, the riblets had been submerged in water for up to a total of 22 hours. No degradation of drag reduction performance was observed.

A sheet of riblet film, 0.305m wide by 0.481m in the streamwise direction, was attached to the flat plate with the leading edge of the film at $x=0.184$m and the trailing edge at $x=0.665$m. For control measurements, the plain vinyl of the same dimensions was attached in the same location. The adhesive film, either riblets or smooth vinyl, will be referred to as the test surface in this report. Figure 1 shows the location of the test surface on the test plate.

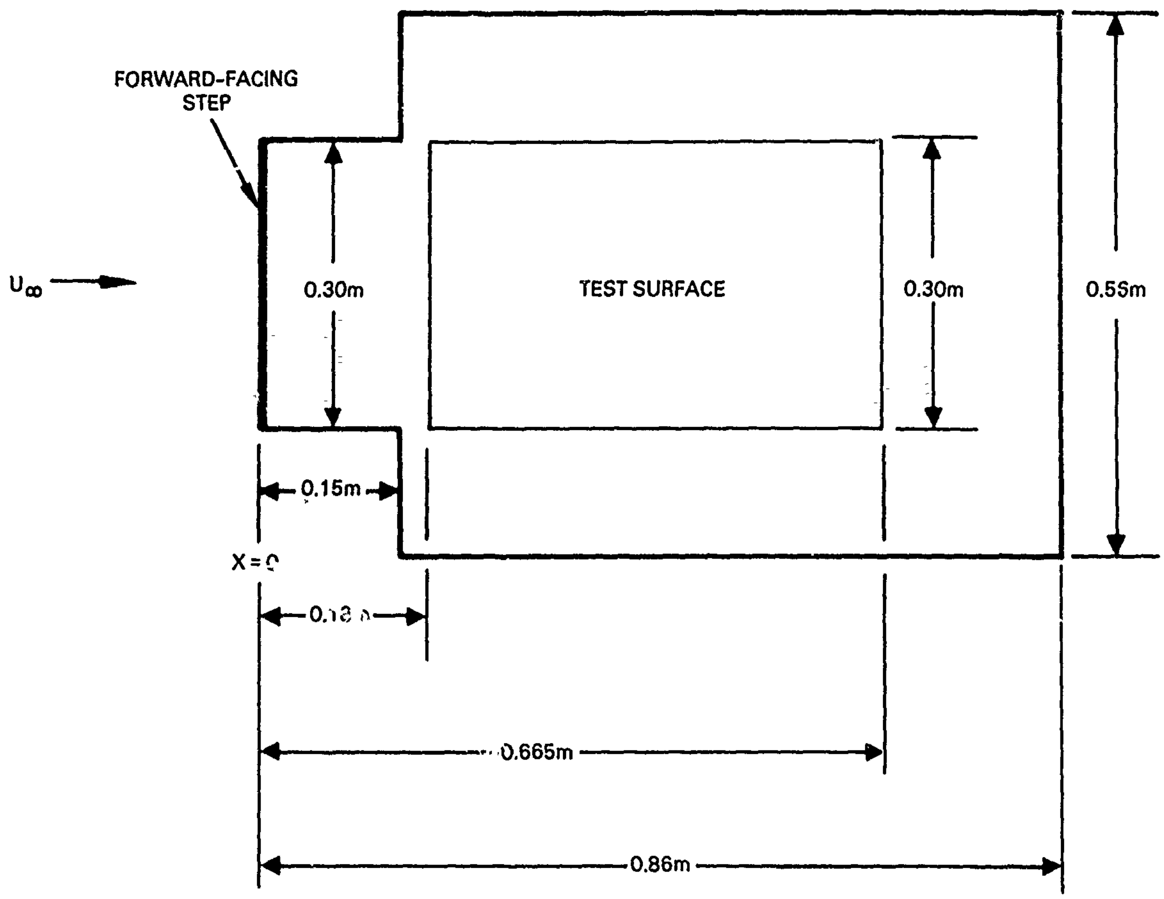


Figure 1. Test plate.

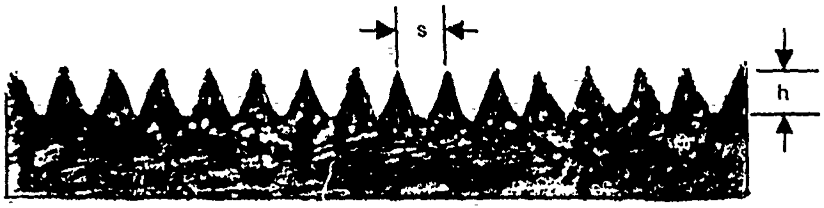


Figure 2. Photograph of riblet cross-section with h=s=0.003 inch.

## BASELINE TESTS

Velocity measurements with the control test surface in place were performed to ensure the presence of a zero pressure-gradient, fully turbulent boundary layer in the measurement region. The velocity profile data shown in figure 3 were obtained at x=0.320m, 0.524m, 0.651m, and 0.778m, and are presented in terms of $u/U_e$ vs. $y/\theta$. The collapse of the data on a single curve represents good similarity of the profiles over the measurement region. Figure 4 shows a profile of $u'/U_e$, the fluctuating streamwise velocity component, obtained at x=0.216m, nondimensionalized by the edge velocity, and compares it to the generally accepted flat plate data reported by Klebanoff [reference 9].

In addition to the $(y/\theta, u/U_e)$ profiles, plots of $(u^+, y^+)$ were made using the skin friction coefficient, $C_f$, calculated from empirical relationships. A typical $(u^+, y^+)$ plot is shown in figure 5, where $C_f$ was calculated using the Ludweig-Tillman relationship,

$$C_f = 0.246(10)^{-0.678H} Re_\theta^{-0.268} ,$$

where the values of $\delta^*$, $\theta$, and H were obtained by integrating the experimental velocity profiles. The measured $(u^+, y^+)$ profile compares favorably to the universal logarithmic profile, shown in figure 5, given by,

$$u^+ = \frac{1}{0.4} \ln y^+ + 5.0 .$$

The velocity point that is closest to the wall, at y = 0.05mm±.02mm, is the only point in the viscous sublayer region ($u^+=y^+$ region).

The skin friction coefficient from the Ludweig-Tillman equation was also used to calculate the riblet size in wall units, $h^+$ and $s^+$. Note that for the riblets tested, $h^+ = s^+$ since h = s. To calculate $s^+$, velocity profiles were measured 4mm upstream of the leading edge of the test surface, at x=0.179m. The local skin-friction coefficient from the Ludweig-Tillman relationship, the free stream velocity, and the viscosity are used to calculate $s^+$ from

$$s^+ = \frac{sU_\infty}{\nu} \sqrt{\frac{C_f}{2}} .$$

This technique for calculating $s^+$ is not appropriate on or downstream of the riblet surface, because the smooth flat plate empirical relation for $C_f$ is not applicable to the boundary layer that has been affected by riblets.

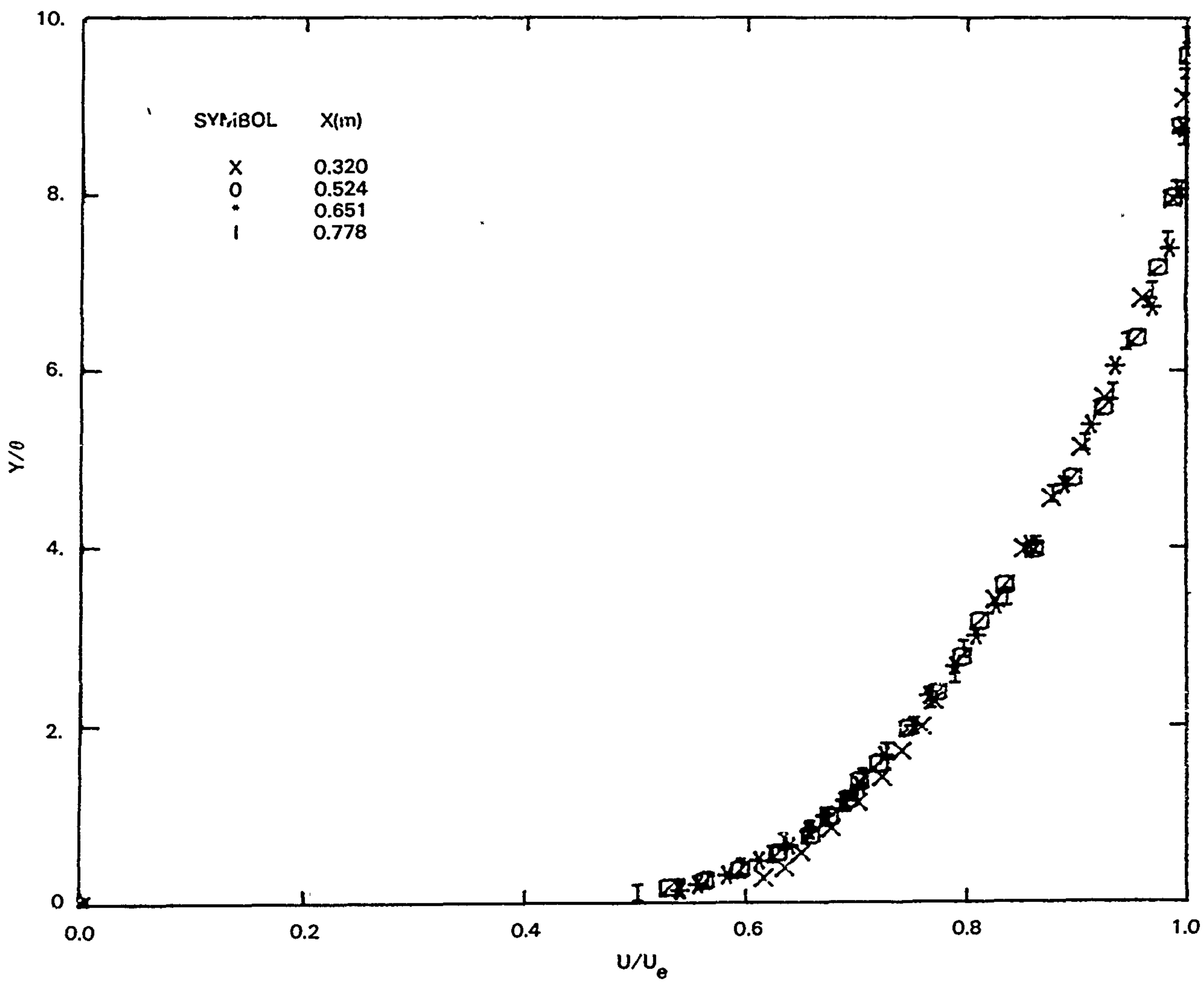


Figure 3. Reference velocity profiles (no riblets).

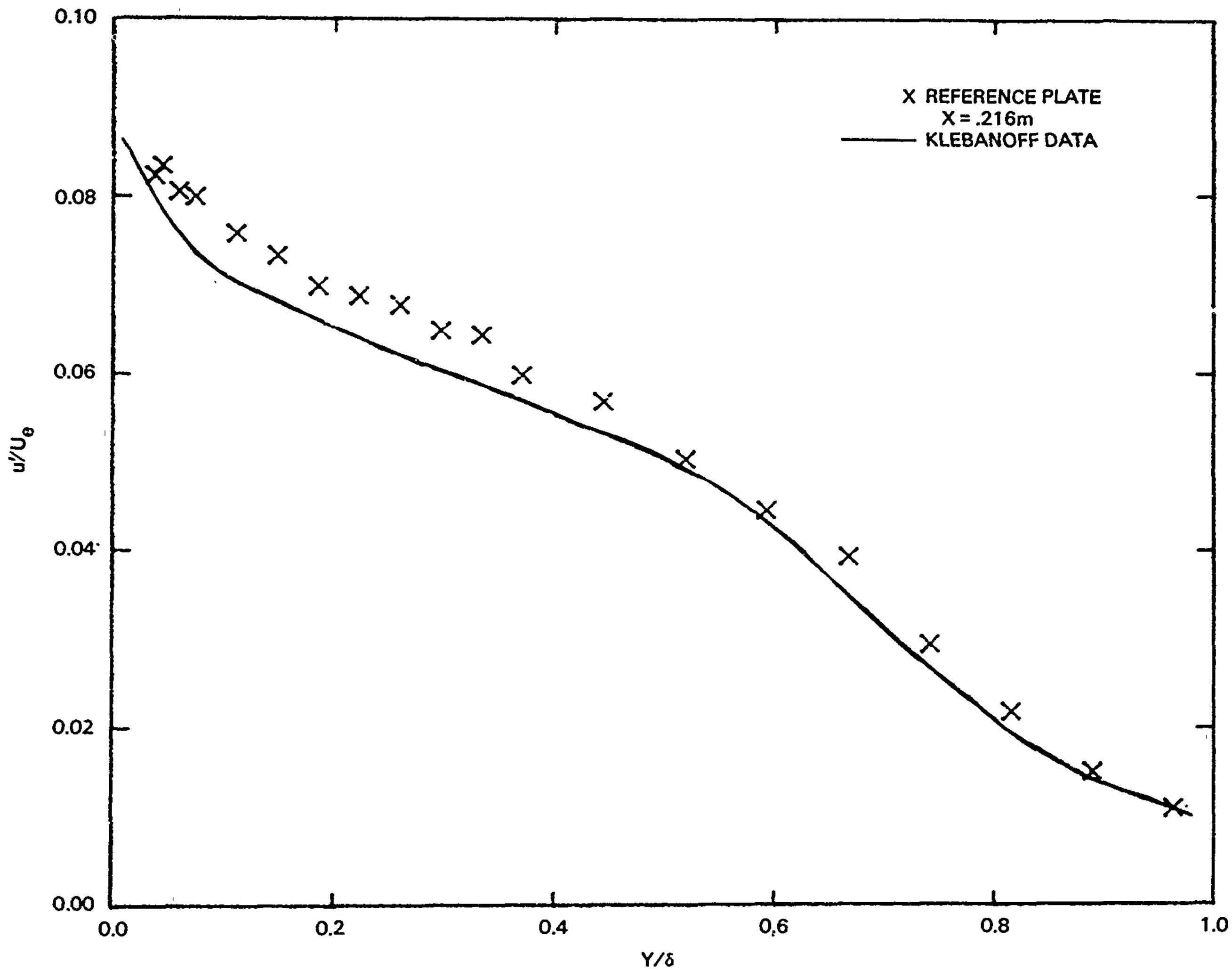


Figure 4. Reference (no riblets).

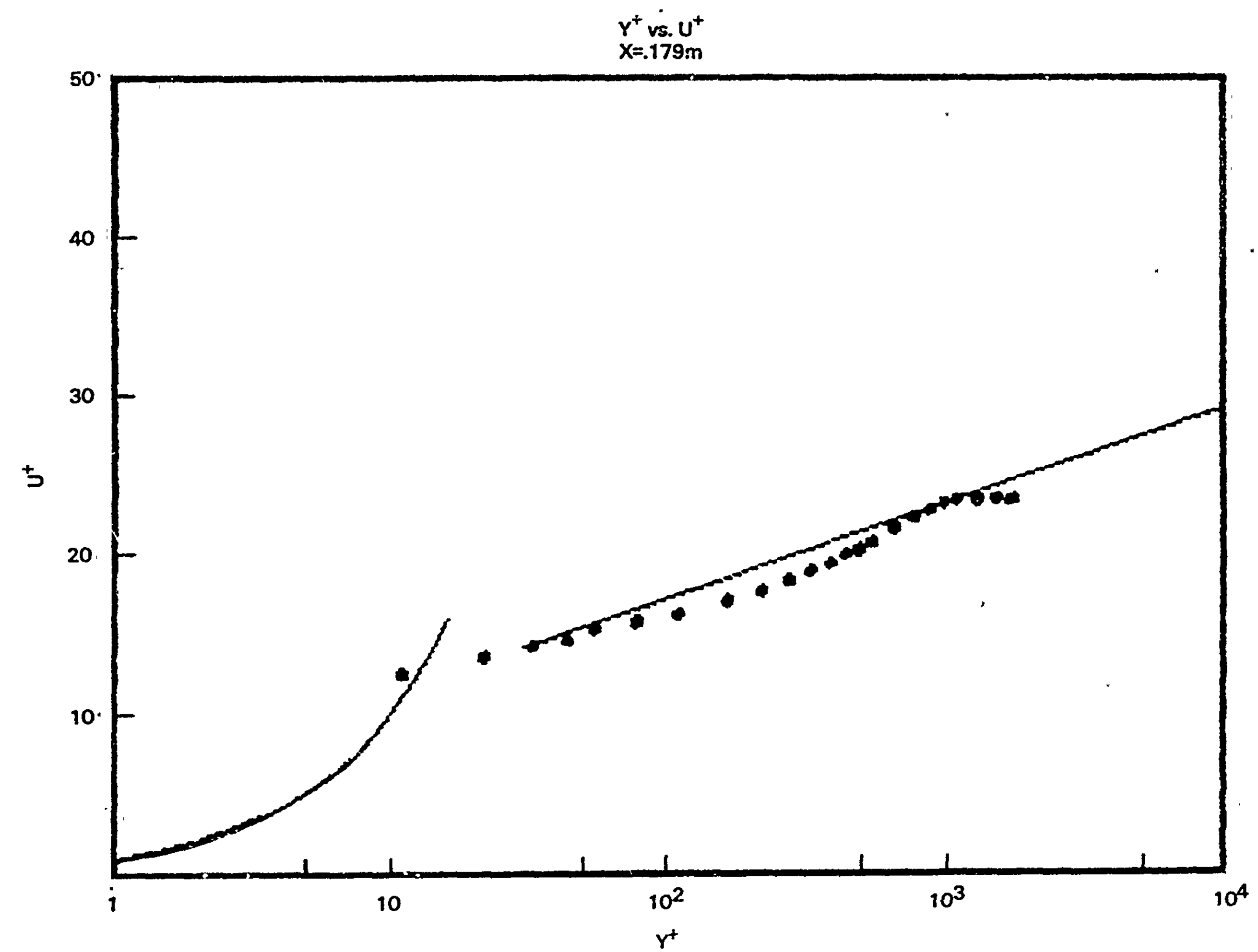


Figure 5. Reference data points (no riblets) compared to the Law of the Wall.

# RESULTS

## MOMENTUM THICKNESS

Each velocity profile was integrated to produce momentum thickness, $\theta$. A comparison of momentum thicknesses is the basis for the drag reduction measurements of this study. In order to compare a momentum thickness downstream from the riblet surface to one downstream from the plain vinyl surface, some adjustments must be made because the water temperature and free stream velocity will not be exactly the same for the two measurements made on different days. The power-law flat plate approximation,

$$Re_\theta = 0.03497\ Re_x^{4/5}\ ,$$

can be rearranged to

$$\theta = 0.03497\ \frac{x}{Re_x^{1/5}} = 0.03497\ \frac{\nu^{1/5}}{U_\infty^{1/5}}\ x^{4/5}\ .$$

In order to compare two momentum thicknesses at the same x-location measured on different days, all measured $\theta$s are adjusted to the same $\nu$ and $U_\infty$. All measurements were adjusted to a viscosity of $1.05 \times 10^{-6} m^2/sec$, which corresponds to 18°C. The measurements are also adjusted to the exact free stream velocity that was attempted, either 2.0, 3.0, 3.5, 4.0, 4.5, 5.0, or 6.0m/sec. The equation used to adjust momentum thicknesses, then, is

$$\frac{\theta_{adjusted}}{\theta_{measured}} = \left[\frac{\nu_{18C}}{\nu_{measured}}\right]^{1/5} \left[\frac{U_{\infty,measured}}{U_{\infty,exact}}\right]^{1/5} .$$

Figure 6 is a plot of adjusted momentum thickness for $U_\infty = 3.5$m/sec. Five spanwise values at $x = 0.70$m (35mm downstream from the test surfaces) are shown for comparing the riblet surface to the control surface. One can see the effect of the riblet film in reducing the momentum thickness. The increase in momentum thickness at spanwise distances from the plate centerline (z=0.0) is due to the spreading of the jet in the open jet test section. At all of the spanwise measuring stations, the drag-reducing effect of the riblets can be seen.

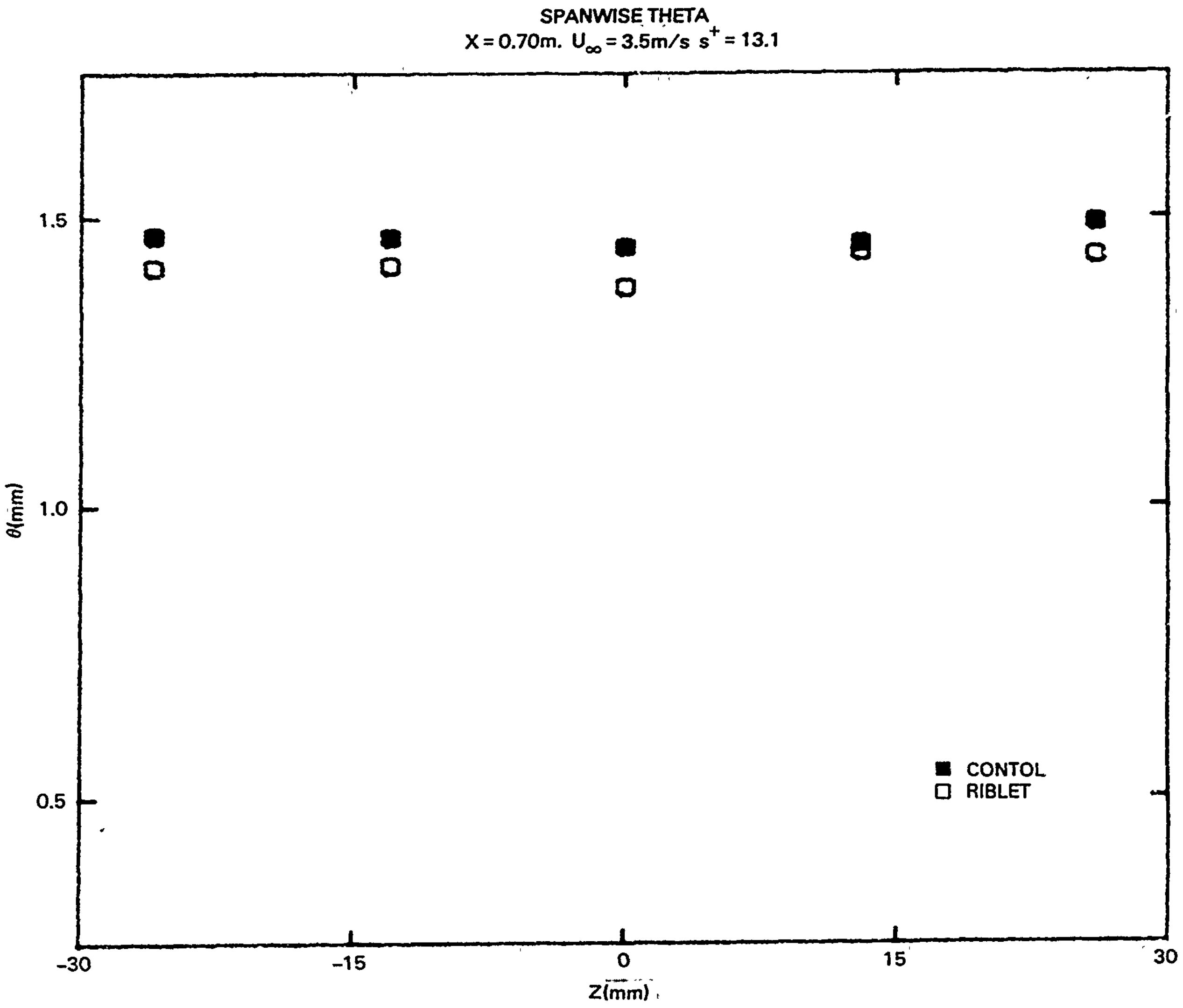


Figure 6. Momentum thickness (theta) vs. spanwise distance (z) measured downstream from test surfaces.

## DRAG CALCULATIONS

The drag on the flat plate was calculated using

$$D = b\rho U^2_\infty \theta \ .$$

The drag reduction over the test surface portion of the plate can be represented as

$$\%DR = \frac{(D_t-D_l)_c - (D_t-D_l)_r}{(D_t-D_l)_c}$$

where the subscripts are t = to the trailing edge of the test surface, l = to the leading edge of the test surface, c = control surface, r = riblet surface. Recognizing that if adjusted momentum thicknesses, as described in the previous section, are used so that $b\rho U^2_\infty$ is a constant, and that the drag upstream of the leading edge of the test surface is the same for riblet and control surfaces ($D_{l,c} = D_{l,r}$), the drag reduction equation reduces to

$$\%DR = \frac{\theta_{t,c} - \theta_{t,r}}{\theta_{t,c} - \theta_l} \ .$$

Trailing edge momentum thicknesses were measured at x = 0.700m, which is 35mm downstream from the trailing edge of the test surface. Velocity profiles closer to the trailing edge are not used because the small step down from the film to the plate may affect the profile shape. However, for the purpose of calculating drag reduction over the length of the test surface film only, the momentum thickness is adjusted so that it corresponds to $\theta$ at x=0.665m, the actual trailing edge of the test surface, using the flat plate approximation relating $Re_x$ and $Re_\theta$ given in the previous section. The same method was used to adjust momentum thicknesses measured 4 to 15mm upstream of the test surface to correspond to the leading edge. This flat plate approximaton may not be perfectly accurate for the region downstream from the test surface that has been affected by riblets, but it is more accurate than treating the area between the trailing edge and the measuring station as if it were covered with riblets. In addition, these adjustments to $\theta$ are very small compared to the change in $\theta$ over the 481mm length of the test surface.

The drag reduction results are shown in figure 7 as a function of riblet size in wall units. The values of $s^+$ correspond to the leading edge of the test surface; $s^+$ will increase by about 9% from the leading edge to the trailing edge of the test surface. The drag reduction percentages in figure 7 are calculated from the momentum thickness measurements on the plate centerline (z=0.0). The maximum measured drag reduction is 8.1%, which occurred for $s^+$=13.1. If a curve is drawn between data points, the region of positive drag reduction is seen to extend from approximately $s^+$=7 to $s^+$=20. Outside of this range, the riblets will be likely to increase, rather than decrease, the surface drag. These results are in good agreement with the bulk of data for v-groove surfaces in aerodynamic and hydrodynamic experiments.

The uncertainties in the measured quantities, velocity, and y-position were used to calculate an uncertainty in momentum thickness of ±1.1% of the measured value. Based on this, the error bands on percent drag reduction (%DR), shown in figure 7, range from ±2.5% to ±2.9%, depending on the Reynolds number. The uncertainty analysis also points out that as the x-direction length of riblet material is decreased, the uncertainty in percent drag reduction increases. For this reason, the maximum possible length of riblet material was used.

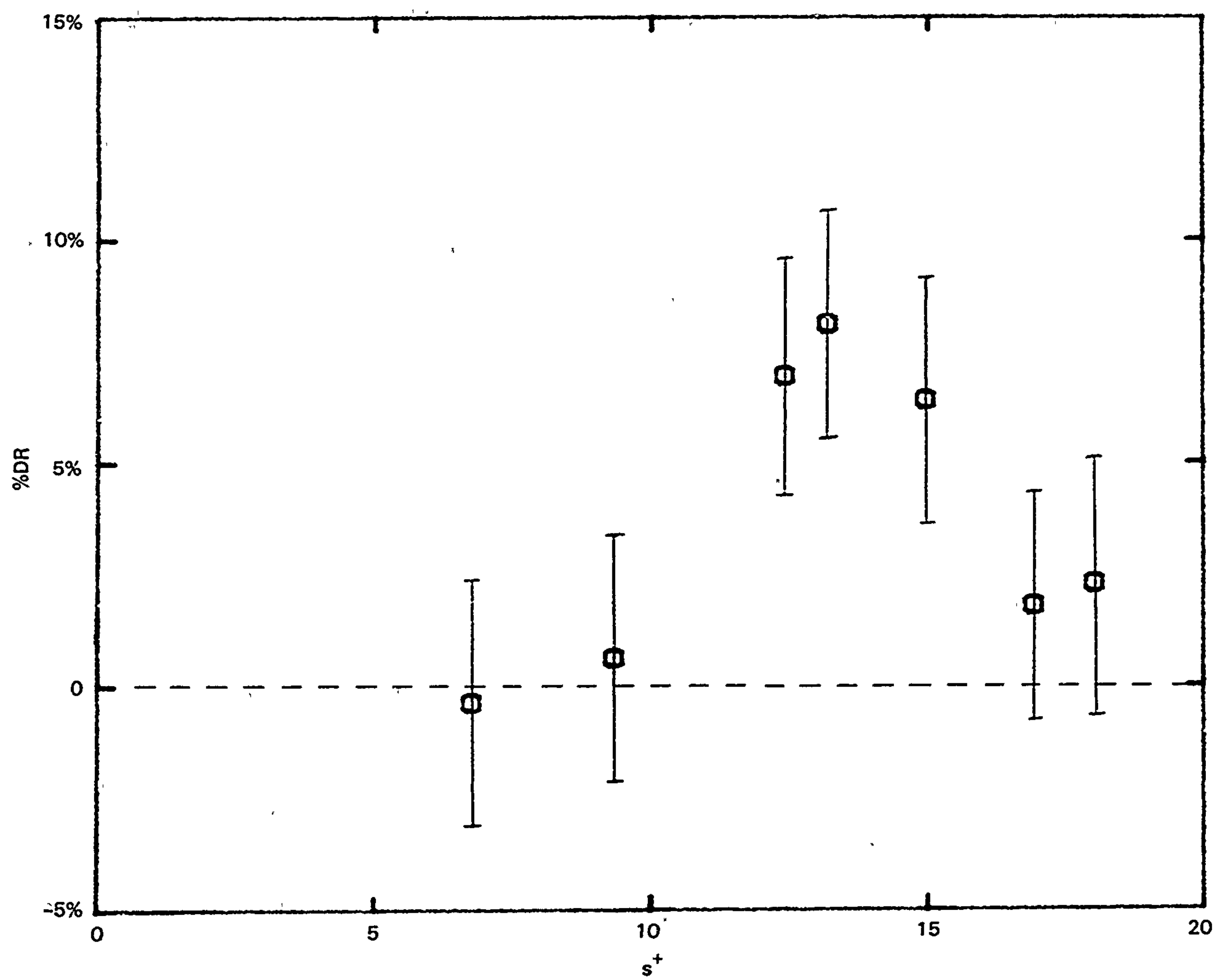


Figure 7. Drag reduction vs. $s^+$(0.003 — inch riblets).

## VELOCITY AND TURBULENCE PROFILES

Profiles of the mean and fluctuating components of the streamwise velocity were measured over the riblet film, as well as downstream from the film. However, because of the uncertainty in choosing a y=0 position for the grooved surface, the profiles over the riblets are not included here. Figures 8 and 9 show profiles measured at x=0.70m (35mm downstream from the trailing edge of the test surfaces). The mean velocity profile (figure 8) shows a region of increased velocity downstream from the riblets compared to the smooth test surface for $y/\theta$ from 0.04 to 0.6. For $y/\theta$ greater than 0.6, the velocities downstream from the riblets are approximately equal to the velocities downstream from the smooth surface.

The corresponding turbulence profile (figure 9) does not present as clear a picture, but it does illustrate some observed trends. The scatter associated with the rms measurements is particularly large in the near-wall region, and is probably due to interference of the laser with the test plate. For $y/\theta$ from 0.08 to 0.4, $u'/U_e$ is suppressed for the riblet case as compared to the smooth test surface. For $y/\theta$ from 0.4 to 1.0, $u'/U_e$ for the riblet case tends to be larger than or equal to that for the smooth test surface case. For $y/\theta$ greater than 1.0, $u'/U_e$ measurements for the two cases are coincident.

## CONCLUSIONS

The results of this experiment are in agreement with the bulk of other measurements of drag reduction using v-groove riblets. The findings show that the vinyl riblets manufactured by the 3M Company, which were originally developed for aerodynamic applications, will perform equally well in water. The measured drag reduction of 8% will correspond to a velocity increase of 2% for a vehicle under constant power. The riblets were quite durable and showed no degradation in performance over the time that the experiment was conducted. Since very long duration use without inspection of the surface could be a potential problem, the most practical Navy application at this time may be to torpedoes. Improvements in fuel economy as well as vehicle speed are possible using this simple, passive, drag reduction system.

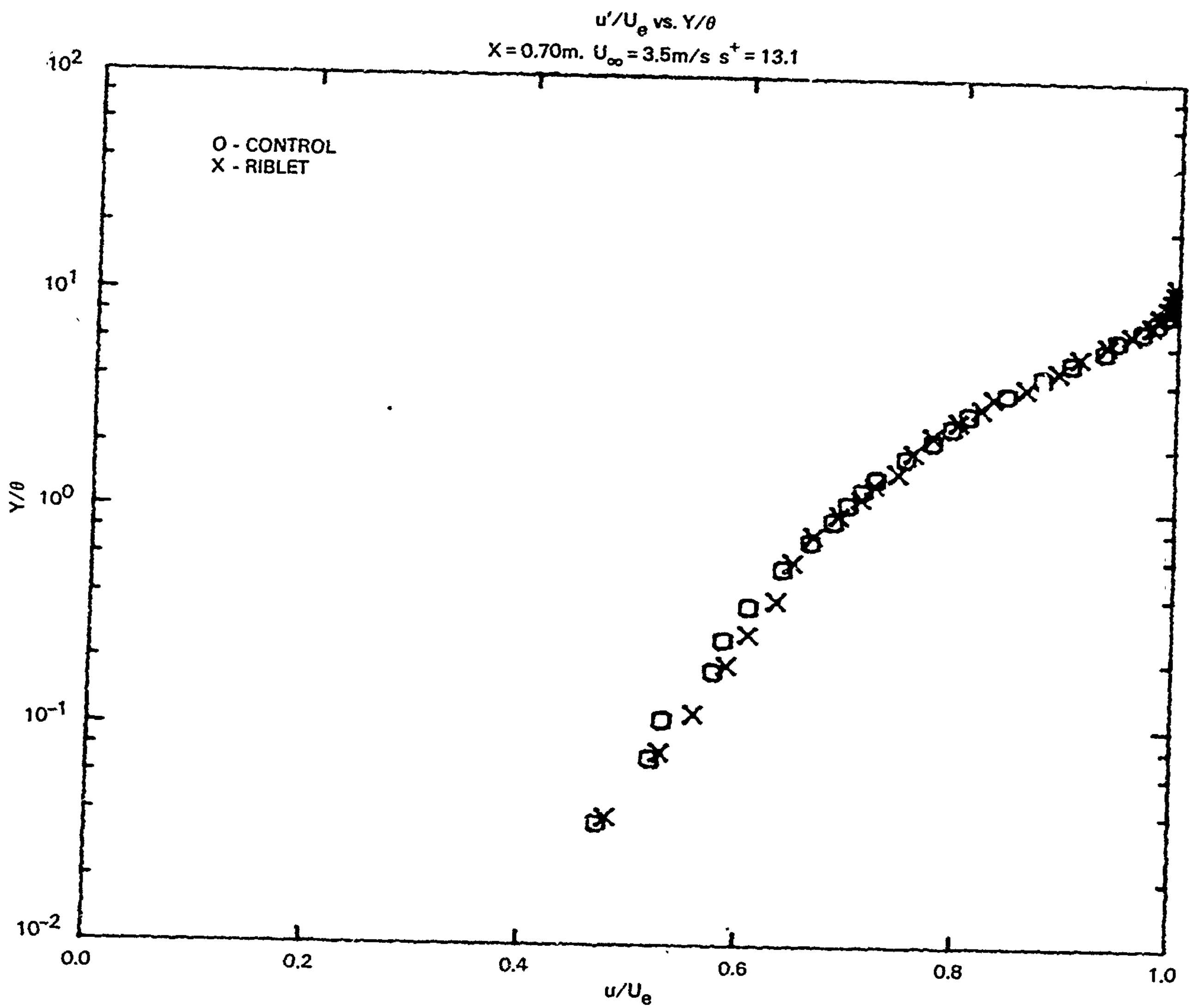


Figure 8. Mean streamwise velocity vs. distance above the plate.

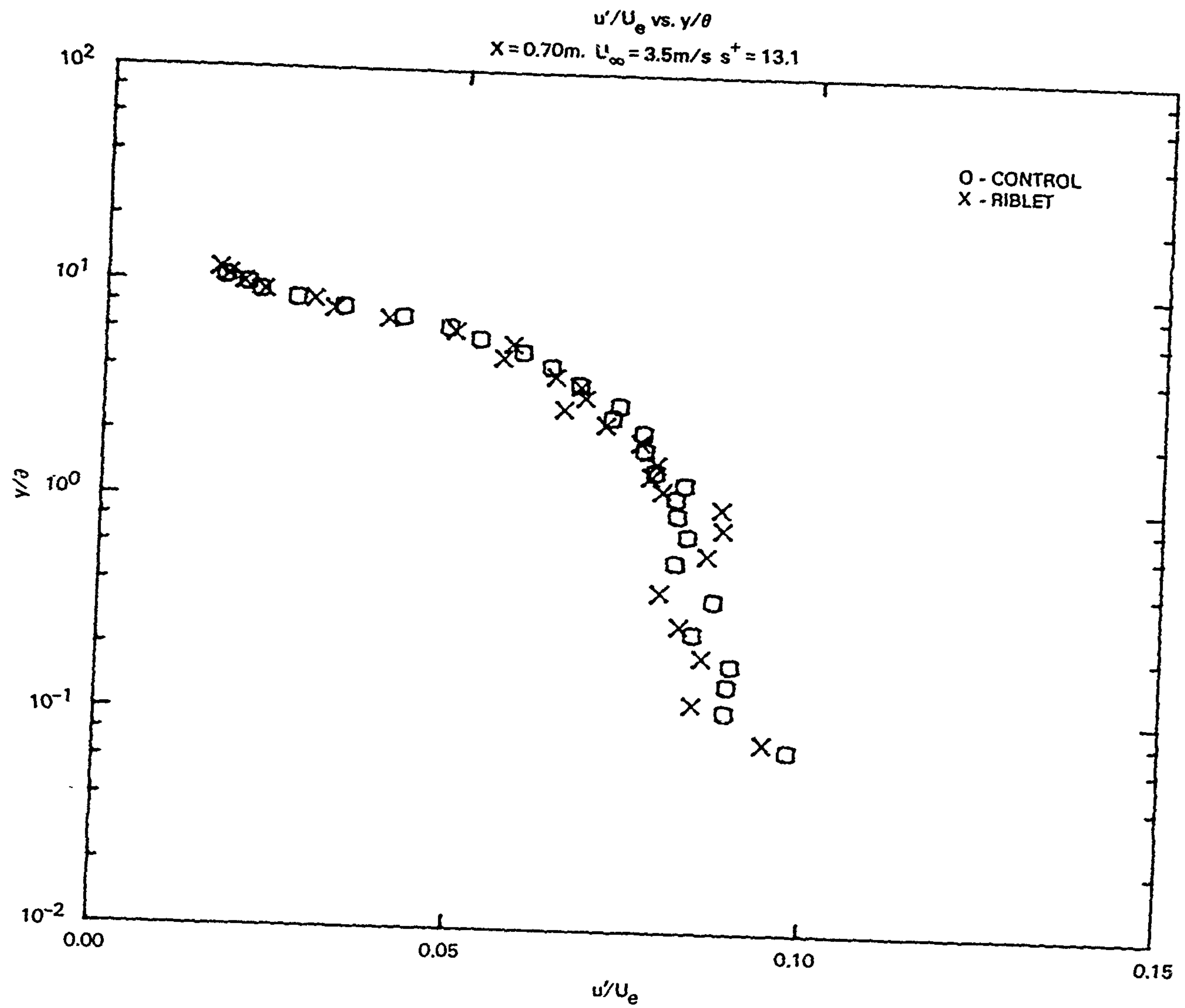


Figure 9. *Fluctuating component of streamwise velocity vs. distance above the plate.*

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